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ON ACHIEVING COLD ANTIPROTONS IN A PENNING TRAP*

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I Introduction

Precision "Geonium" studies of a single antiproton in a Penning trap would be a natural continuation of such studies on more readily available particles[1]. At the University of Washington, single electrons and positrons have been trapped for precision g-value measurements[2] and small numbers of protons have been trapped to measure the ratio of the proton and electron masses[3]. The major new challenge offered by antiprotons is in getting them from the high energies at which they are produced down to the very low energies where trapping can be carried out. Once a small cloud of antiprotons is trapped (and eventually just a single antiproton), a logical first experiment is to measure the antiproton mass and then to measure the ratio of the proton and antiproton masses by measuring the cyclotron frequencies of these particles in the same trap. The properties of the trap can be well established ahead of time via studies with protons. Long trapping times have already been repeatedly demonstrated (eg. greater than 9 months for a single electron by us[4]) so that an antiproton lifetime greater than the existing 32 hours[5] would be soon established. Many other studies would also be possible but these are sufficient motivation for this note since our purpose is to discuss trapping techniques.

Basic production of antiprotons at CERN and FERMILAB provides between 10^7 and 10^8 antiprotons per main accelerator cycle ($\lesssim 10$ s) of $\approx 10^{13}$ protons[6]. However, these antiprotons initally fill a phase space volume $\approx 10^2$ eV–s at a mean energy of 4–10 GeV which is poorly matched to the phase space volume of a trap. For example, a Penning trap with a 6 Tesla magnetic field and a 10 volt well depth contains only $\approx 10^{-6}$ eV–s. Even if one assumes no phase space density dilution in deceleration and transfer this amounts to less than 1 antiproton per accelerator cycle into the trap. Fortunately, the LEAR ring at CERN is able to bridge this gap significantly and in what follows we shall begin with the antiprotons which can and are being produced at LEAR.

The most direct approach to trapping antiprotons requires several stages of deceleration and cooling in progressively smaller "rings", with the minimum cooled phase space density ultimately determined by space charge limitations. Space charge directly limits the number of cooled $\bar{p}$'s available in a given ring at low energy via the intrabeam scattering mechanism (IBS)[7]. The cooling mechanism of choice at the lowest $\bar{p}$ energies would be electron cooling, since it is energy tunable and very compact. On the other hand space charge limits the current in a low velocity e^- beam consistent with low electron temperature. Therefore beam storage/cooling is not possible at the lowest energy stage ($\lesssim$100 KeV $\bar{p}$ kinetic energy). One method would be direct, transient, deceleration from the last storage/cooling stage at a few hundred KeV. Unfortunately such a scheme still requires an auxiliary ring to bridge the gap, at LEAR for instance, from 5–10 MeV to several keV to allow trapping. The direct approach might allow the trapping of very large number of antiprotons in one filling of the trap[8].

The current state of proton/electron trapping sensitivity at Washington, however, requires only small numbers ($\lesssim$ 100) of $\bar{p}$ be trapped in order to achieve high signal to noise ratios. We therefore investigate here a $\bar{p}$ trapping scheme based on stopping foils which, in the simplest case, require no auxiliary decelerator/cooler past a LEAR (or equivalent) stage. Cooling of the trapped particles could be accomplished via the damping provided by an external resistor as in all of the other experiments[8]. The rate for this cooling would be rather low, even in the most ideal case[8], and likely would be much lower when the electrostatic anharmonicity of such a trap is realistically considered. We thereby examine here a possible alternate cooling scheme, electron cooling with a buffer gas of cold electrons, in order to improve the cooling rate.

II $\bar{p}$ Facility Requirements

We discuss trapping $\bar{p}$'s in the context of working at LEAR, in order to use its well defined beam parameters. We use the lowest energy LEAR $\bar{p}$ energies (5–10 MeV) with beam parameters in in Table I[9].

TABLE I Assumed LEAR Parameters

$\bar{p}$ momentum	141 mev/c
$\Delta p/p$	$\pm 0.8 \times 10^{-3}$
ϵ_H	7 mm mrad
ϵ_v	3.5 mm mrad

It seems likely, however, that the $\approx 30 Mev$ kinetic energies already realized at LEAR would be sufficient. Such parameters are modest in the sense that only the initial (600 mev/c) stochastic cooling is called upon. $N_{\bar{p}}$ is kept well below any limit where IBS becomes significant. We calculate the IBS total emittance blow up time[7], τ, to be much larger than one hour for 10^7–$10^8 \bar{p}$ for the parameters of Table I. After cooling at 600 mev/c the beam is decelerated to 141 mev/c and a longitudinal segment is fast ejected. No further cooling is required (although the scheme can, of course, be improved upon — as we discuss later) and the enhancement which would be offered by RF bunching is not required.

We would need a pulse of antiprotons only occasionally during our loading period, perhaps every ten to twenty minutes. Once loading was successfully completed, no more antiprotons would be needed for long periods of time. In fact, the apparatus with the antiprotons could conceivably moved to another room. The beam would never be required for long sustained periods of time because no statistical data taking would be done.

III Antiproton Trap Loading

The Penning trap used for load antiprotons is represented in figure I and Table II. For the most precise experiments, a small number of antiprotons would be transferred to a second smaller trap which is specifically designed for optimal anharmonicity reduction[10]. The initial electrostatic well for the loading trap is considerably deeper than usual (2 KeV) in order to trap a significant energy bite of the $\bar{p}$ "beam". Consequently the trap dimensions are also larger. After the injected $\bar{p}$'s are cooled the well potential would be reduced to $\lesssim$ 100 volts to accomodate the standard cell potential source necessary for precision work. Injection into the trap is accomplished by keeping the injection endcap electrode at ground until $\bar{p}$'s from the head of the $\bar{p}$ bunch have completed one full cycle (axially) through the trap ($\lesssim$ 130 ns). The injection cap electrode is then stepped down to -4 KV, thus trapping all $\bar{p}$'s which exited the degrader with 2 KeV $\leq E_{K,z} \leq$ 4 KeV. Notice that the 130 ns transit time $\equiv \tau_I$ sets the required LEAR bunch length ($=$ 5.9 meter at 141 mev/c or 7.4%of LEAR circumference).

TABLE II Trap Parameters

Axial Half Height (z_0)	1 cm
Radial Half Height (ρ_0)	1 cm
Endcap – Ring Potential Diff.	4 KV
$\bar{p}$ "Beam" Entrance Aperture Radius	1 mm
Magnetic Field	$\approx$ 6 T
ν_z ($\bar{p}$)	11.4 MHz

Table II lists the nominal parameters of the trap we envision using. $\bar{p}$'s are degraded from 10 meV to mean zero energy in the surface layer of the injection endcap electrode. $\bar{p}$'s emerging into the trap volume with an axial kinetic energy between 2–4 KeV will be trapped. We note that the Larmor radius for 4 KeV (worst case) $\bar{p}$'s in 6 Tesla is 0.5 mm, so that the final trapped $\bar{p}$ distribution radial extent is determined entirely by the spot size on the degrader (thin target — see section IV).

Degrading the $\bar{p}$ energy at the last possible instant serves two important purposes. First, we take full advantage of the radial containment of the magnetic field. Second we can maintain the "sealed trap" concept which has proven so successful in Seattle single particle studies. A slight alternative would be a *flat* degrader followed immediately by a mesh electrode face. The combined requirement of UHV seals and of an electrically floating endcap electrode makes the construction somewhat more complex than in usual practice. We note, in this respect, that the endcaps could be at ground while the ring electrode would pulse *positive*. This would result in r_f being reduced by approximately $\frac{1}{2}$ while the accepted axial kinetic energy slice would be 0–2 KeV (see section V).

The $\bar{p}$ capture cross section[11] determines the vacuum we must achieve in our trap. For instance $\sim 1 \times 10^{-11}$ torr will give a capture rate of one per day for $5°K$ thermalized Helium. The *quiescent* pressure expected from the *sealed* type trap of figure 1 submerged is $<< 10^{-14}$ torr[13]. No evidence of collision is detected in the existing vacuum[14] enclosures used now for the precision single particle experiments. However surface perterbing action such as e^- impact from he field emission point or ionizing radiation from $\bar{p}$ annihilation or the accelerator environment must be taken into account. Ultimately a direct $\bar{p}$ storage time study is called for. We expect operation of the field emission point to be the worst spoiler. However the trap can easily include a cold labyrinth gas trap opposite the emission point.

IV Beam Optics – Degrading

In order to concentrate the initially trapped $\bar{p}$'s as much as possible to allow fast electron cooling (section VI) we choose a $\bar{p}$ spot size on degrader as small as possible compatable with LEAR transverse emittance. Injection must be precisely along the trap solenoid axis. We assume that a minimum separation of 2 m must be maintained between trap and the last focusing beam line element. Probably this spacing can be reduced since only precision studies are sensitive to magnetic perterbation.

(Alternatively, electrostatic lenses are possible here. Clearly a precision servoed beam line is required to aim down the magnet axis.

For a 1 mm radius degrader aperture the emittances of table I indicate a 4 cm diameter beam at the 2 meter distant last focus elements. The horizontal plane will be twice as spread out: half the beam is lost. However the solenoid fringe field provides a significant focusing itself, full benefit from which depends on accurate entrance beam alignment. Several low pressure proportional chambers could be included to servo in the beam alignment (in conjuction with fast electrostatic steering elements).

The degrader will be of a high purity low Z material to minimize induced radioactivity and multiple scatter. Our schematic indicates a monolithic degrader/endcap. Though simplest, this is not essential and may change after detailed fabrication and material property consideration. For Aluminum the range is about 250μ, enough for sturdy mechanical design. Apparently little is known about the stopping power for *negative* massive charges below $v_{ion} \approx \alpha c$; while for 3 KeV $\bar{p}$'s $v_{\bar{p}} = 0.22\alpha c$. Within mechanical tolerances, uncertainty in this very low energy range of stopping powers does not alter the gross range predicted (or measured) for protons. On the other hand the details of energy loss from $\approx$ 100 KeV to $\approx$ 3 KeV (last $\approx 1\mu$ of range) could conceivably lead to unexpected $\bar{p}$ yields. For instance it is clear that by the time $\bar{p}$'s reach velocities $\lesssim \alpha c$ their velocity distribution must essentially be isotropic. No notion of "beam" will hold, and an anomolous number will be lost to capture. We will allow for this by incorporating an additional factor 2 dilution in estimates of the final trapped number of $\bar{p}$'s. Notice that $0.22\alpha c >> \alpha c\sqrt{m_e/m_p}$ which is the threshhold for significant capture cross section[11].

The longitudinal emittance (Table I) translates to a $\bar{p}$ energy spread of 950 KeV at the degrader. The spread due to straggling is about $\frac{1}{3}$ this[12]. Therefore our 2 KeV acceptance slice represents a dilution of 475.

V Trap Efficiency, $\bar{p}$ Trapping Time, and Possible Improvements

Table III summarized the loss fractions we assume starting from a coasting LEAR beam (Table I).

TABLE III $\bar{p}$ Loss Factors

LEAR Revolution period / τ_I at 10 MeV	= 14.5
Accepted energy slice: 960 KeV / 2 KeV	= 480
Isotropic Degraded Distribution	≈ 2
Transverse Acceptance Match	4
Net Dilution	4.4×10^5

Thus for $\lesssim 2 \times 10^7 \bar{p}$ coasting in LEAR at 10 mev we expect to trap ≈ 20 $\bar{p}$, a quite adequate number. Nonetheless, the trapping is inefficient: most of the $\approx 10^7 \bar{p}$ will be captured in the trap electrodes. One advantage of a phase space conserving deceleration scheme would be to greatly increase this efficiency[8]. The total induced radioactivity will be negligible since the total number of stopped $\bar{p}$'s for a complete experiment will be small. Single charges are routinely kept in our traps indefinitely. Therefore the bulk of the $\bar{p}$ dose will acrue during tuning.

Many features of the $\bar{p}$ transfer from LEAR to trap are improved if further cooling processes and/or steps become available at LEAR. In particular a LEAR low energy ***electron*** cooling stage helps us three ways. First, the $\bar{p}$ beam phase space density is considerably increased. Second, entrainment of the $\bar{p}$'s by the ***highly stable*** electron beam allows for stable beam tuning (both in energy ***and*** position). This would greatly simplify tuning the exact range through the necessarily ***fixed*** degrader. Alignment of the beam line down the solenoid axis would be more reproduceable. Third, the momentum spread in LEAR would be so small ($\lesssim 10^{-4} \Delta p/p$) that tight bunching with still small energy spread is possible. These improvements could reduce the net dilution to only ~ 250!

VI Electron Cooling

In principal the $\approx$ 2 KeV trapped $\bar{p}$'s could be cooled for precision work by external resistor damping as has been demonstrated in the previously mentioned experiments and recently calculated in some detail[14]. We investigate here the possibility of attaining much faster damping via collisions with a cold electron cloud introduced by standard methods into the center of the trap after a potential well is established. This electron cloud would serve only as an electron cooler. After the $\bar{p}$'s cool, these electrons would be ejected (by R.F. excitation) from the trap.

Thus we consider the properties of such a cloud in the 2 KeV potential well (Table IV).

TABLE IV Cold Electron Cloud Parameters

cloud radius	$\approx$ 2mm
cloud density	2×10^7/cc
maximum space charge field	720 volts / meter
Debeye length	4×10^{-3}cm
η	0.18
fast Coulomb log	9.2
electron temperature	$\approx 5°K$

The cloud radius is determined by the $\bar{p}$/degrader spot size to be $\approx$ 2 mm. This radius is maintained by the standard "magnetron cooling techniques"[15]. Electrostatic considerations show that the shape will be aproximately shperical for the symmetric trap we consider here. Then the maximum electron density n_e is constrained such that the space charge field $<<$ trap field. Choosing $n_e = 4 \times 10^7$/cc gives a worst spacecharge to trap field ratio of $\lesssim 1\%$. Such a density for electrons thermalized in the usual way[16] gives a Debeye length $\lambda_D \lesssim 4 \times 10^{-3}$ cm $<<$ cloud radius. This insures a well defined cloud edge.

We avoid the issue of "adiabatic" $\bar{p}$–e^- coulomb collisions by estimating the electron cooling time solely on the basis of the "fast" collisions (impact parameter / $v_{\bar{p}} \lesssim e^{-}$cyclotron period)[17]. This criteria is a stronger limit on the maximum impact parameter than λ_D, so we use it to arrive at a ("fast") coulomb logarithm $L = 9.2$.

The electron cloud is very cold so that we have the "classic" electron cooling situation $v_{e^-} << v_{\bar{p}}$ for which the damping rate formula[18]:

$$\lambda = -8\pi c r_e r_p L n_e \eta \beta_{\bar{p}}^{-3}$$

may be employed (η being the fraction of time the $\bar{p}$'s spend in the cloud during their axial oscillation). The values summarized in Table IV then yield $\lambda = 0.18/s$.

Proven sideband cooling techniques can be used to insure that the unstable magnetron motion of the $\bar{p}$ does not increase in radius because of the collisions to the point where antiprotons are lost from the trap. Moreover we observe that an electron cloud which does not entirely fill the trap cannot drive the antiprotons entirely out of the trap. In more detail, although each e^{-}-$\bar{p}$ collision reduces the $\bar{p}$ kinetic energy, the *angular* deflection of the scattered $\bar{p}$ allows significant *diffusion* of the magnetron orbit radially out from the center of the trap. Since the magnetron energy is $<<$ the cyclotron energy (initially $r_m \approx$1 mm, $r_c \approx$0.45 mm while $E_m \approx$0.08 ev and $E_c \approx$ 3 KeV) the magnetron motion will not be initially cooled. In the transverse plane (cyclotron plane) a $\bar{p}$ will suffer "multiple" scattering:

$$\theta_{rms}^2 = 8\pi r_{\bar{p}}^2 L n_e \beta_{\bar{p}}^{-4} l$$

where $l = \bar{p}$ path length segment and L is the *same* Coulomb Log used for λ. Let $l \equiv \eta v_{\bar{p}}/\lambda$, yielding $\theta_{rms}^2 \equiv m_e/m_{\bar{p}}$. The net diffusion of r_m will then be:

$$\Delta r_m \equiv r_c \theta_{rms} \quad \sim 0.01mm$$

Since r_c progressively shrinks as the cooling progresses the total diffusion of r_m is not qualitatively larger than the above.

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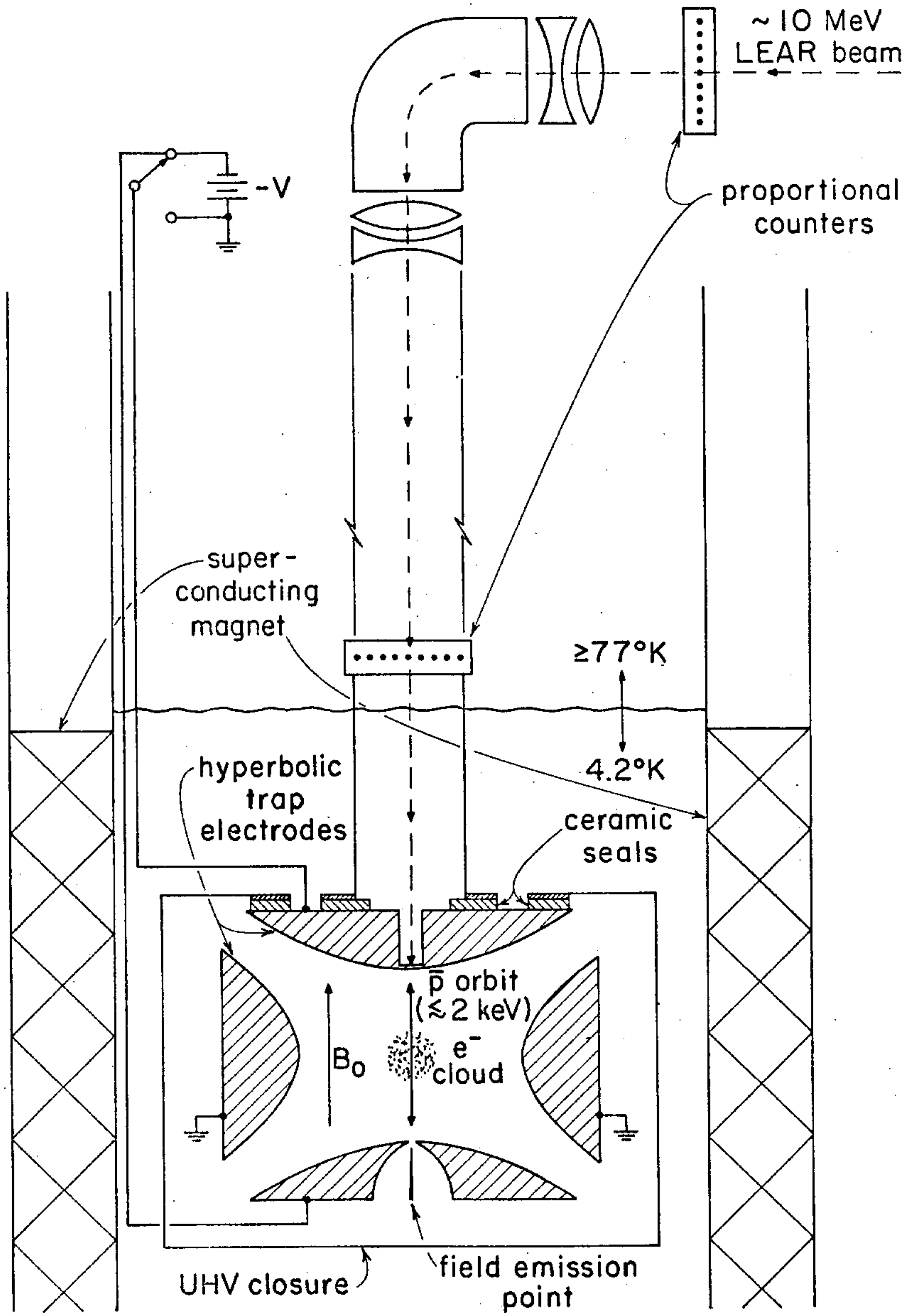
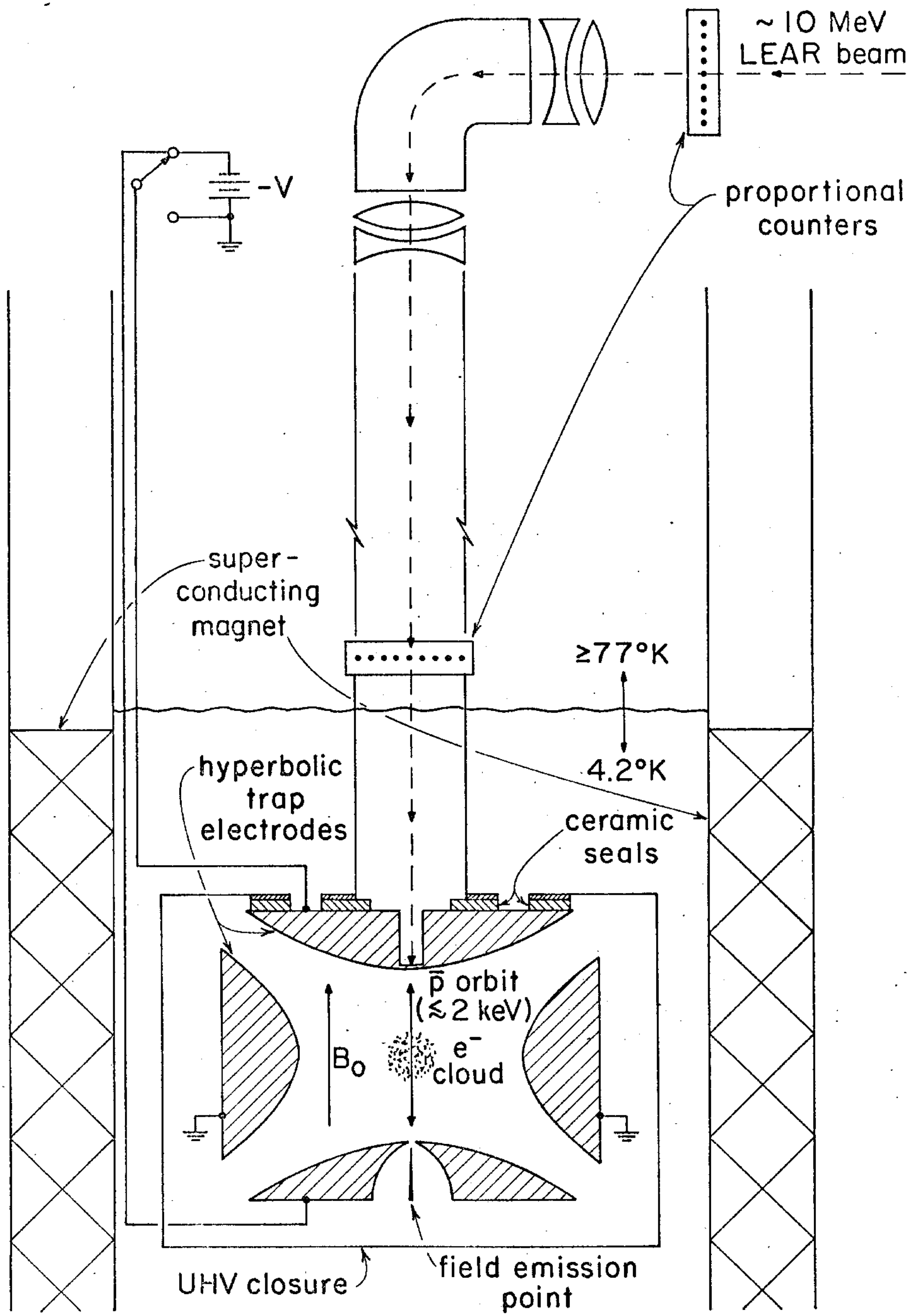

~10 MeV
LEAR beam
proportional
counters
-V
super-
conducting
magnet
≥77°K
4.2°K
hyperbolic
trap
electrodes
ceramic
seals
p̄ orbit
(≲2 keV)
B0
e⁻
cloud
UHV closure
field emission
point

Figure 1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